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# Cosmic Ray Muon Imaging

Chris Morris

*Los Alamos National Laboratory*

10-June-2014

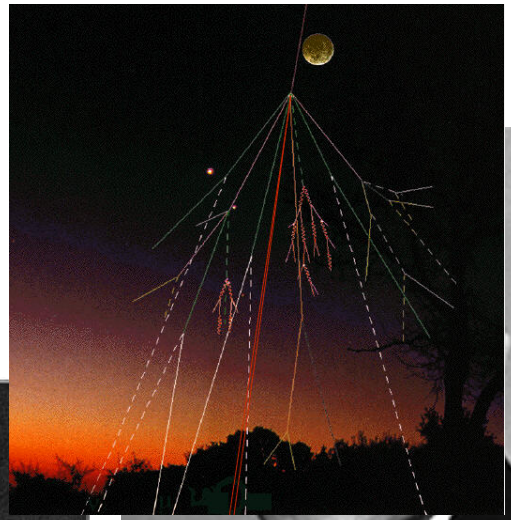
The cosmic ray flux of about ~1 particle per $cm^2$ per minute at the earth's surface is composed predominately of mu-mesons ($\mu^{\pm}$). E. P. George was the first use cosmic ray muons for radiography. George measured the stopping rate of muons in order to determine the overburden of a mine tunnel. This technique has since been used for a variety of geological and archeological investigations] We have researched using the multiple scattering of muons for radiography. In addition to providing much more sensitivity than stopping, multiple scattering provides 3-d information, enabling tomography. This technology has recently been chosen for use in studying the damaged cores of the Fukushima Reactors.

# Radioactivity, three discoveries-three Nobel prizes

**Wilhelm Conrad Roentgen**
Discovered x-rays in 1895
First Nobel prize in physics 1901

**Antoine Henri Becquerel**
Discovered Radioactivity in 1896 shared the Nobel prize in physics with **Pierre and Marie Curie**, 1903

**Victor Franz Hess**
1910-1913 showed cosmic rays come from outside the solar system. Shared the Nobel prize in 1936 with C.D. Anderson



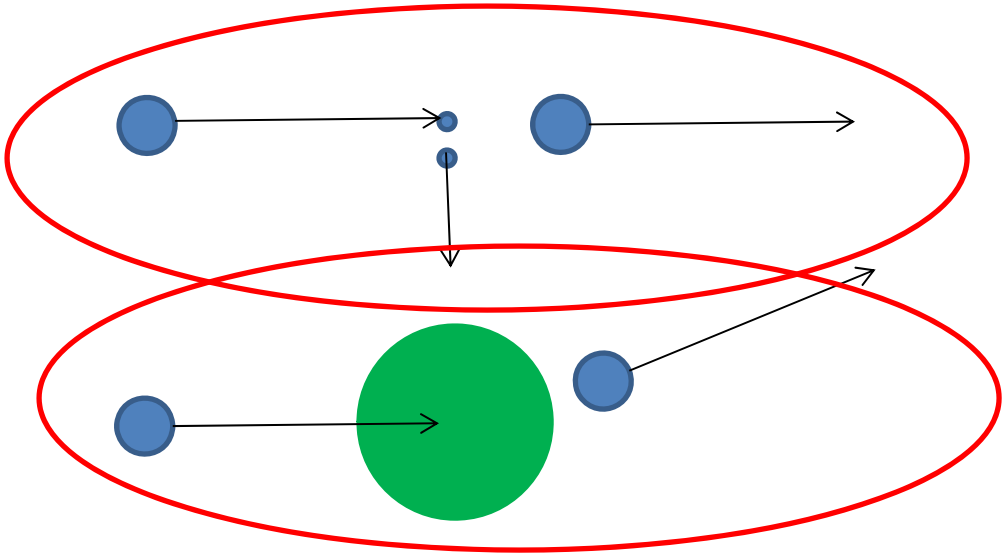
Flux at earths surface is predominately muons

- Letons
- Time dilation

# Muon Interaction with Matter

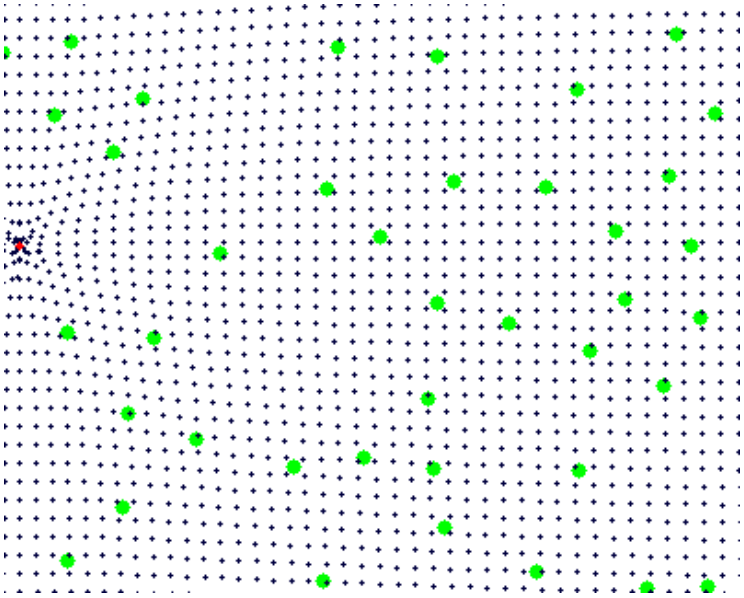
## Kinematics

| particle | mass (MeV) |
|---|---|
| $e^{\pm}$ | 0.5 |
| $\mu^{\pm}$ | 105 |
| p/n | 940 |



## Coulomb Interaction

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \csc^4\left(\frac{\Theta}{2}\right).$$



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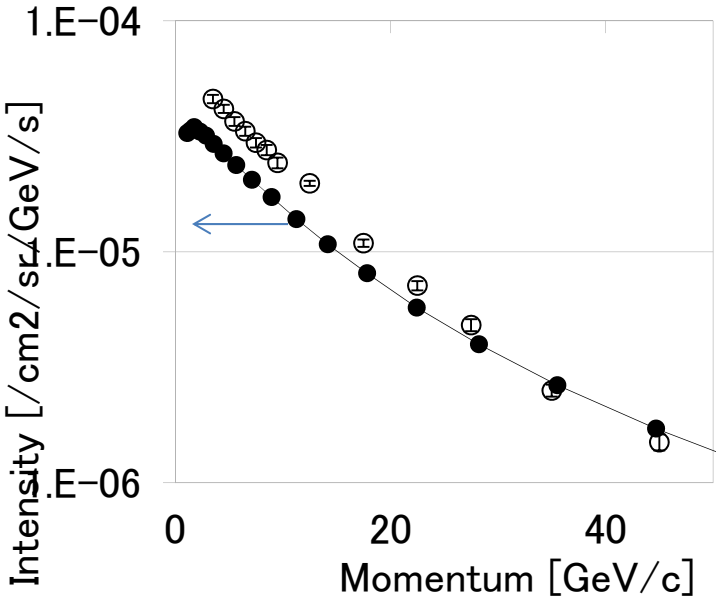
# Energy Loss

$$\frac{dN}{dx} = \frac{dN}{dE}\frac{dE}{dx}$$

$$\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right)\right]$$




# Multiple Scattering

$$\frac{dN}{d\theta} = \frac{1}{2\pi\theta_0^2}e^{-\frac{\theta^2}{2\theta_0^2}}d\Omega$$

$$\theta_0 = \frac{14.1}{p\beta}\sqrt{\frac{L}{X_0}}$$

$$\frac{1}{X_0} = \frac{K}{A}\left\{Z^2\left[L_{rad} - f(Z)\right] + ZL'_{rad}\right\}$$

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| | dx/dE cm/GeV | x cm |
|---|---|---|
| Reactor Core | 731.9 | 8.7 |
| Concrete | 254.1 | 15.8 |
| Fe | 88.4 | 9.5 |
| water | 502.5 | 36.0 |

# Stopping Cosmic Radiography

Commonwealth Engineer, July 1, 1955 455

## Cosmic Rays Measure Overburden of Tunnel

● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

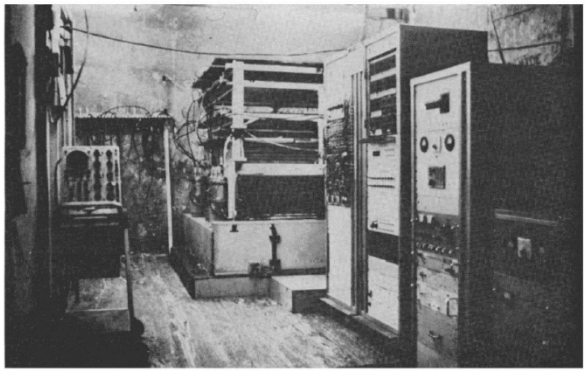
**Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described**

By Dr. E. P. George*
University of Sydney, N.S.W.

## Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy,



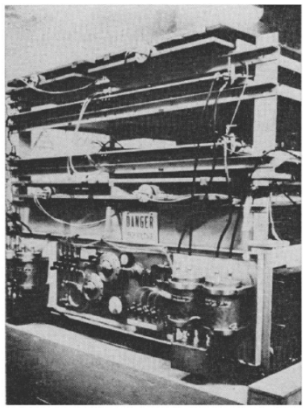


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.



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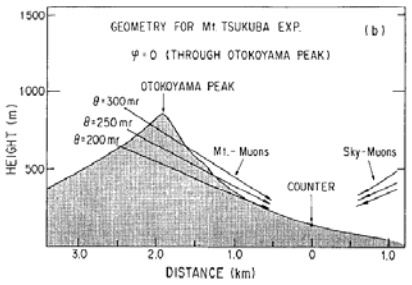
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

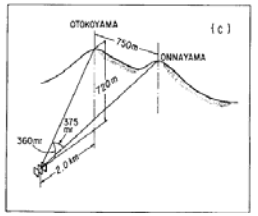
## Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction

K. Nagamine [a,b,*], M. Iwasaki [a], K. Shimomura [a], K. Ishida [b]

[a] *Meson Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo, Japan*
[b] *Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan*

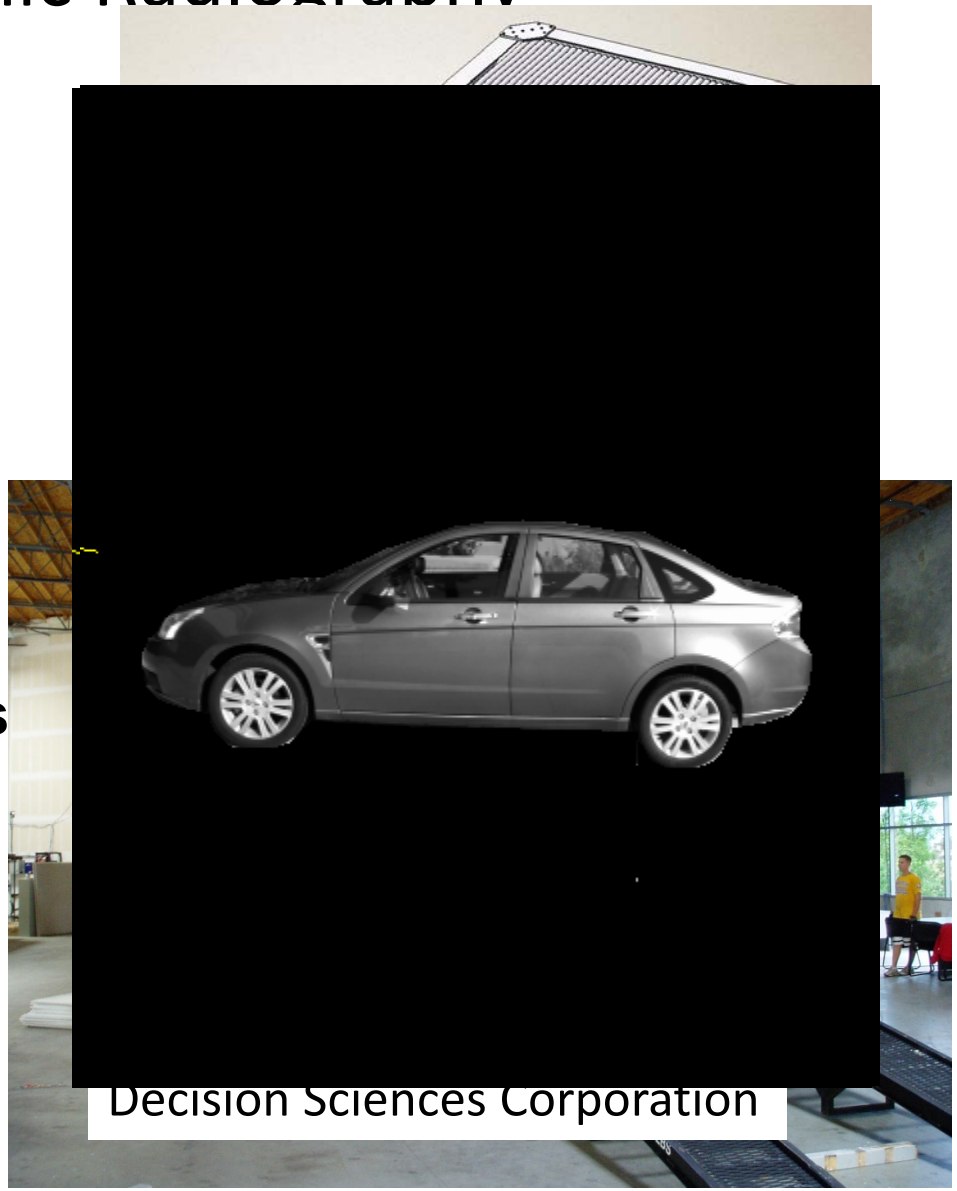
Received 4 July 1994; revised form received 12 September 1994



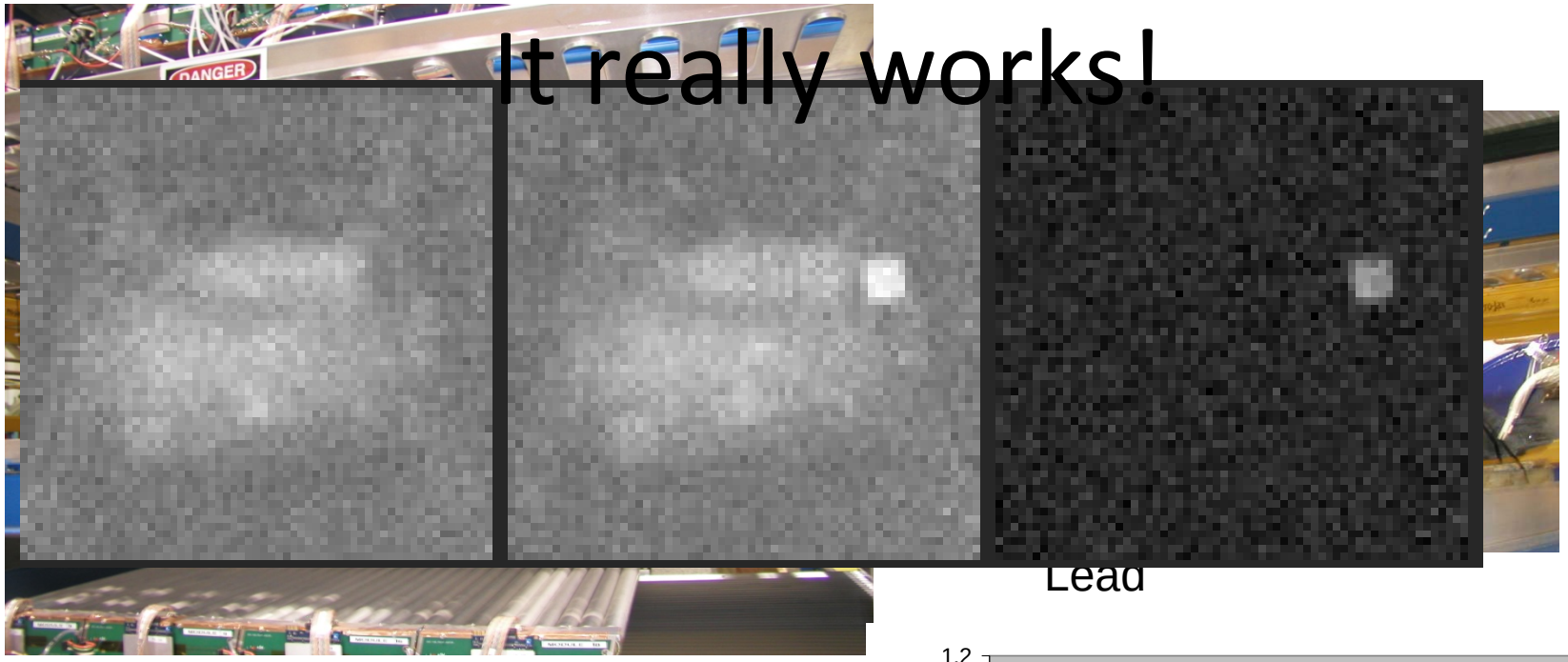
# Scattering Cosmic Radiography

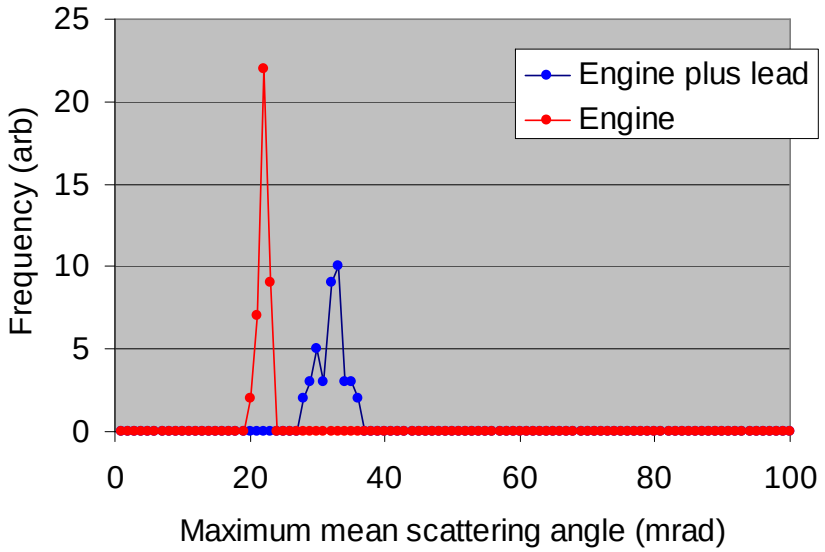
- **Technical approach:**
  - **Measure passive radiation**
  - **Use muons to generate "scattering density" image**
    - » Built in momentum measurement
    - » Automatic calibration using flux through empty detector
  - **Combine signals to identify threats**
- **Advantages over other methods**
  - **No radiation**
  - **Simple technology**
  - **Inexpensive**
  - **Can penetrate thick cargos**
  - **Automatic Identification**

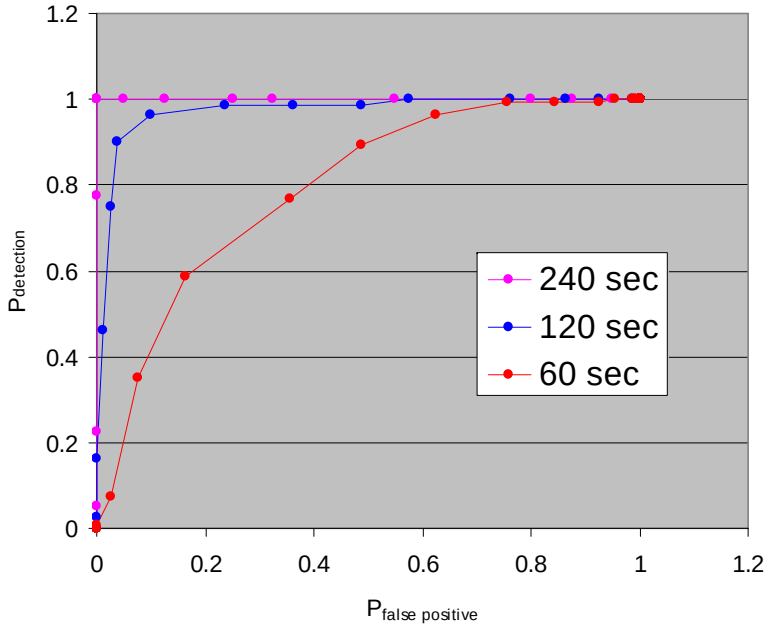


Decision Sciences Corporation

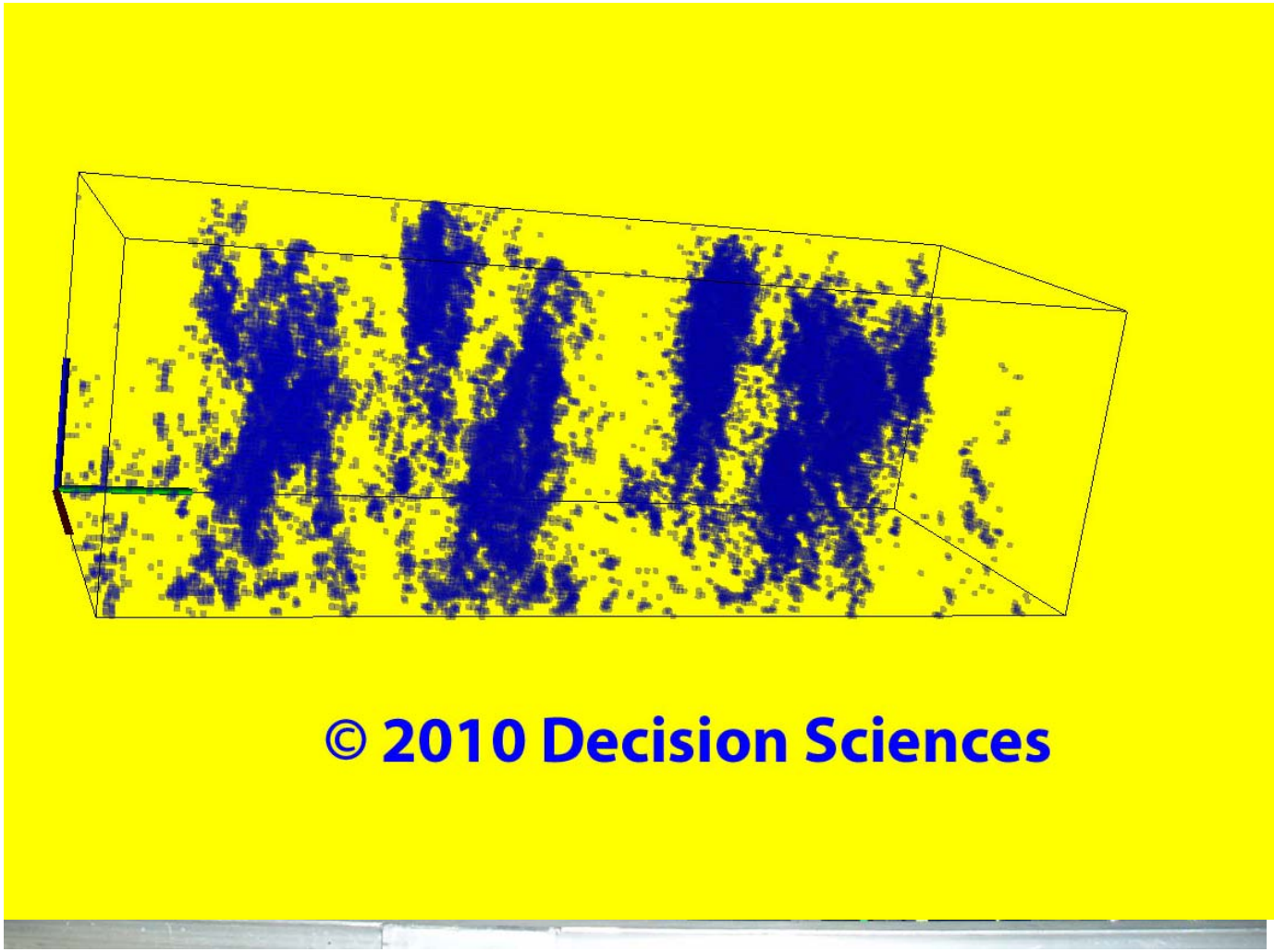
# It really works!



# Decision Sciences



# Decision Sciences First Installed Commercial Muon Scanner at Freeport in the Bahamas

# Radiography of Fukushima reactors

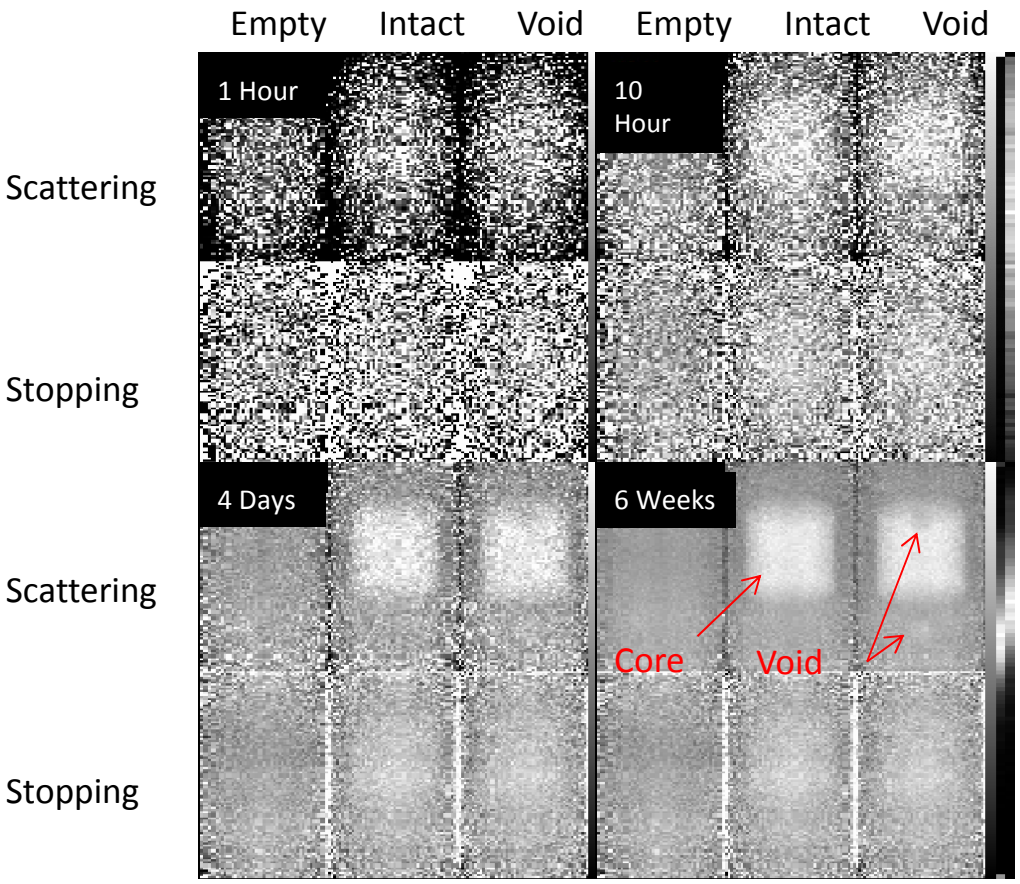
11 March 2011 Tohoku Great Earthquake

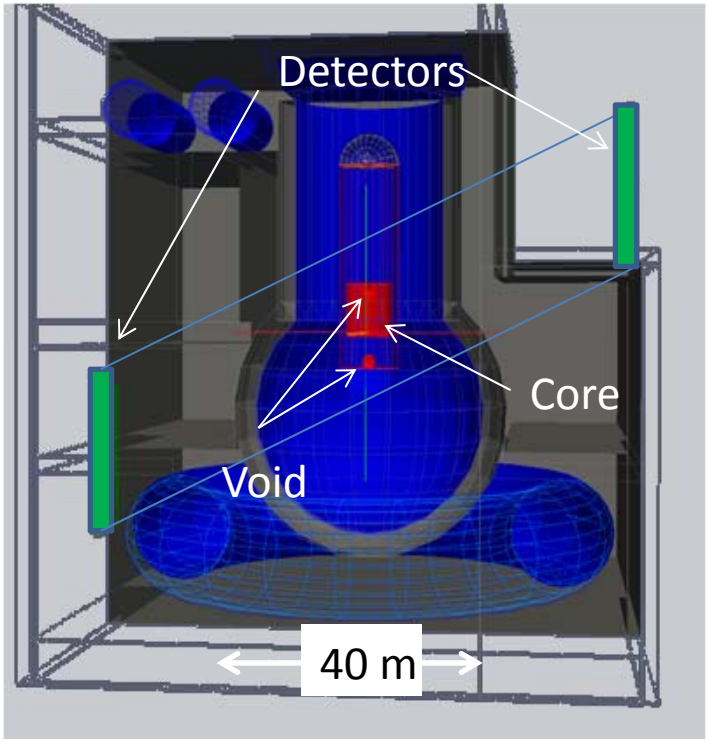
18500 Deaths due to the earthquake and tsunami.
Economic loss ~$275 billion

2 weeks after the earthquake Cas Milner suggesting using muon scattering to look at the cores.

Three reactors melted down.
Clean up estimated to take 40 years.
(No prompt deaths due to radiation exposure;
No increased cancer rate; radiation deaths estimated to be negligible. Clean up cost ~$15-100 billion

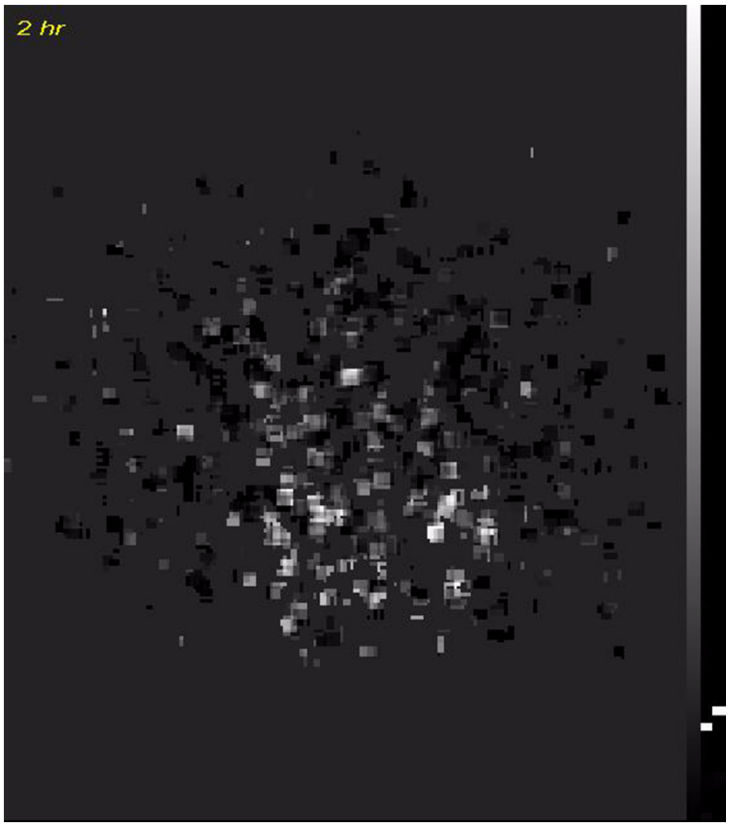
# Geant Simulation of Radiography of Fukushima reactors



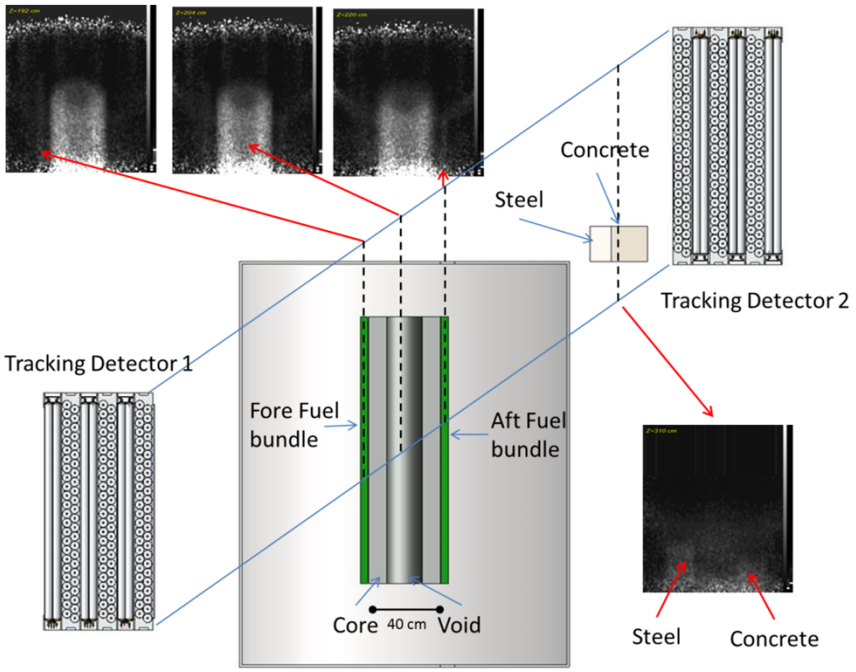



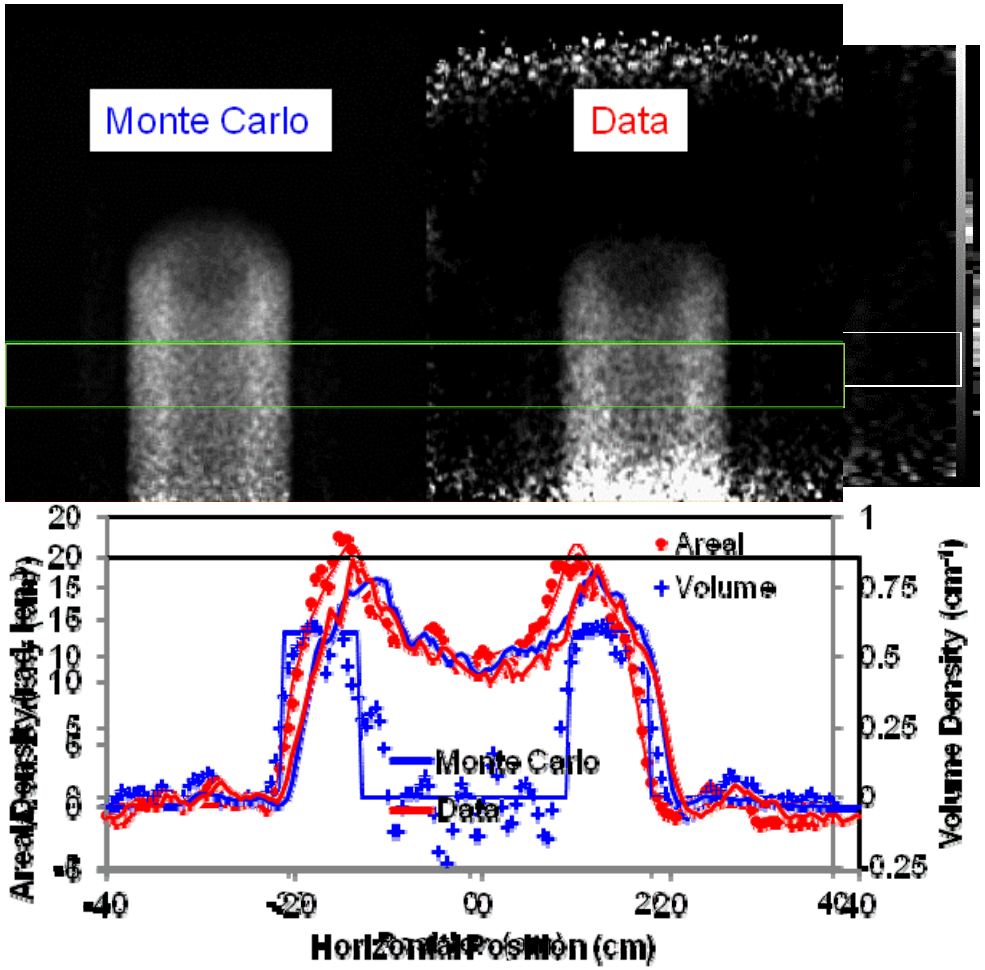

- Scattering Cosmic radiography can be used to image the damaged cores
- Stopping radiography is much more difficult

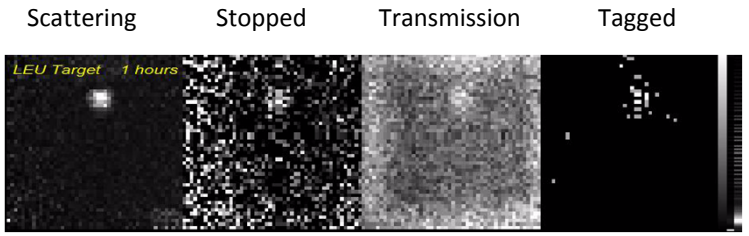
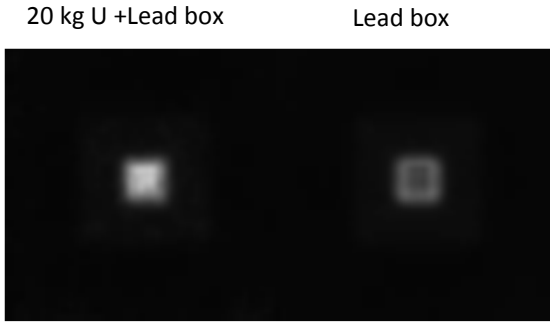
# Results from Toshiba Nuclear Critical Assembly (NCA) Radiography (350 hrs exposure)



# NCA Results


Concrete
Steel
Tracking Detector 2
Tracking Detector 1
Fore Fuel bundle
Aft Fuel bundle
Core 40 cm Void
Steel
Concrete


Monte Carlo
Data
Areal
Volume
Monte Carlo
Data
-40
-20
0
20
40
Horizontal Position (cm)
Volume Density (cm⁻¹)
1
0.75
0.5
0.25
0
-0.25

# Summary

- Cosmic ray radiography
  - Apparatus is simple and robust.
  - In use for border protection (Bahamas)
  - Potential for treaty verification
  - Radiography of Fukushima cores is approved
  - Cosmic rays allow precise assessment (~several %) with 8 weeks of exposure